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Quantification and analysis of CO_2 footprint from industrial facilities in Saudi Arabia

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A R T I C L E I N F O

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A B S T R A C T

The Kingdom of Saudi Arabia (KSA) is among the countries that committed to taking measures to cut greenhouse gas emissions in accordance with the 2015 Paris Climate Agreement. KSA has rolled out the 2030 Vision aiming at creating a more diverse and sustainable economy that cascaded into a series of initiatives, including the circular carbon economy, Saudi green initiative, and the national renewable energy program. Furthermore, KSA has recently announced an ambitious goal to reach net-zero goal by 2060. In its updated nationally determined contribution (NDC), the Kingdom committed to reducing its carbon emissions by 278 million tons of CO_2eq (equivalent) annually by 2030. This ambition is more than a twofold increase versus the previously announced target (130 million tons of CO_2eq). With no current plans to change its hydrocarbon production rates, this reduction in emissions would be achieved mainly through diversifying its energy mix, increasing the efficiency of industrial processes, and deploying carbon capture utilization and storage (CCUS). To achieve this goal, it is vital to establish a detailed register for CO_2 emissions from stationary industrial sources to design optimum and effective CCUS applications. This register includes details about the emission source locations, rates, and characteristics. For the first time, this paper provides a country-wide extensive study that maps out CO_2 emissions from stationary industrial emitters associated with the leading six industries in the country, which are electricity generation, desalination, oil refining, cement, petrochemicals, and iron & steel. Moreover, CO_2 concentrations within the emitted flue gas from these resources are estimated, which is crucial to determine the capture cost. This study aims to provide a vital resource for researchers and policymakers who seek to reduce greenhouse gas emissions by promoting renewable energy, improving the efficiency of existing fossil-fuel-based industries, and evaluating the potential of CCUS in KSA.

1. Introduction

The ever-increasing influx of greenhouse gases (GHG) into the atmosphere from various anthropologic activities is a major environmental challenge facing the globe. CO_2 gas, originating from fossil fuel combustion and industrial processes, represents nearly-two-thirds of total annual GHG emissions globally [19]. For the first time on record, the current CO_2 concentration in the atmosphere at the Mauna Loa observatory has exceeded 420 parts per million (ppm), representing about a 40 % increase relative to the pre-industrial levels [65,72]. This historical growth in atmospheric CO_2 concentrations, increasing at an average rate above 2 ppm per year, results from fossil-fuel combustion and deforestation [23]. Thus, GHG contribution to climate change has become an urgent public and governmental concern [44]. Recognizing the gravity of the situation, 195 countries, as members of the United Nations Framework Convention on Climate Change (UNFCCC), signed the Paris Climate Agreement in 2015. Each member nation is expected to voluntarily contribute to the global effort to mitigate climate change within this agreement by setting its own nationally determined contributions (NDC) [11]. One of the key ambitions of the Paris Agreement is to limit global temperature rise within this century to below 2 °C relative to pre-industrial temperature levels [36,56].

The Kingdom of Saudi Arabia (KSA) is among the nations that signed and ratified the Paris agreement in 2015 [70]. As a member of the

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UNFCCC, KSA submitted its fourth national communication in 2022, prepared by the Saudi Designated National Authority (DNA) in coordination with the relevant ministries and organizations [3]. This official document provides a comprehensive overview of national economic and environmental aspects and estimates for GHG emissions from the public and private sectors. Furthermore, measures and plans taken by the government in response to climate change are also discussed. On the other hand, in the most updated NDC in 2021, the Kingdom has pledged to reduce its carbon emissions by 278 million tons of CO_2eq annually by 2030 [29] and ultimately achieve net-zero by 2060. This ambition is more than a twofold increase over the previous 2015-INDC, which was 130 million tons of CO_2eq [29]. KSA rolled out the [40] program in 2016, which charts the path toward energy and economic diversification [40]. This includes the launch of various initiatives and programs to improve efficiency in industrial processes, reverse to cleaner energy such as natural gas, and promote the use of renewable energies, including solar, wind, geothermal, green and blue hydrogen, combined with carbon capture utilization and storage [8,40].

As part of this reform, the Saudi energy efficiency center has been launched with a mission to improve energy efficiency by targeting the industry, building, and land transportation sectors which account for about 90 % of national energy demand. One goal is to transition to generating 50 % of electricity via natural gas by 2030. The program also includes comprehensive reform, regulations, and policies that stimulate the establishment of local renewable supply chains and industry that deploys various renewable technologies like solar PV, concentrated solar power, wind, geothermal energy, waste to energy, and green hydrogen. The Kingdom's flagship giga-project, NEOM, intends to build massive green hydrogen facilities with a production capacity of 650 tons per day of green hydrogen by electrolysis and 1.2 million tons of green ammonia per year, to be powered by over 4 GW of renewable energy from solar and wind [49].

On another frontier, KSA has promoted and endorsed the circular carbon economy (CCE) as part of the G20 to manage carbon-based economies with reduced emissions. CCE is framed as an extension of a circular economy with a principle of removing CO_2 at the point source or from the atmosphere. Capturing CO_2 at the point source for conversion into value-added products or storage in geological reservoirs is a critical technology to meet the Paris Agreement goals [29,71]. For instance, Saudi Aramco is currently conducting a CCUS project for enhanced oil recovery (EOR), where CO_2 has been injected into Uthmaniyah oilfield at a rate of about 0.8 $MtCO_2$ per year since 2015 [50]. In this project, CO_2 is captured at the Hawiyah Natural Gas Liquids (NGL) plant and transported via an 85 km onshore pipeline to the injection site. Injection occurs in a water-alternative-gas (WAG) mode, where 40 % of the total injected CO_2 volume is expected to remain permanently trapped within the subsurface reservoir [37,38,39]. Another major company, SABIC, is operating a CO_2 capture and utilization plant in Jubail city, which is designed to capture up to 0.5 $MtCO_2$ per year from the production of ethylene glycol and use it in the production of other commodities such as fertilizers [58].

Further implementations of CCUS are directed toward blue hydrogen applications & circular economy, enabling an indirect use of fossil fuel and transforming it into an environmental-friendly alternative [14]. In 2020, Saudi Aramco announced the world's first shipment of blue ammonia – produced from natural gas with CCS in the hydrogen plant in Jubail – to Japan, where it is used to produce emissions-free electricity (Ratcliffe, 2020). This collaborative effort between Saudi Aramco, SABIC, and Saudi Arabian Fertilizer Company (SAFCO) for the production and pilot shipment of 40 tons of blue ammonia demonstrated an example of the blue hydrogen economy enabled by CCUS. About 50 tons of CO_2 were captured, where 30 tons were utilized for methanol and urea production, and the remaining 20 tons were injected into the Uthmaniyah oilfield [55].

Developing an extensive analysis of the CO_2 emissions in KSA is a vital building block to enable and track the Kingdom's ambitious emission reduction goals. The primary objective of this work is to provide a comprehensive quantification of CO_2 emissions in KSA from all major industries, including electricity generation, desalination, petroleum refining, petrochemical industries, cement production, and the iron & steel industry. The cumulative emissions from these categories account for three-quarters of the total CO_2 emissions. In addition, road transportation represents one-fifth of total national emissions; this sector and its impact on the environment has been discussed thoroughly by other researchers [5,4,52]. In this study, publicly available data records for more than 1200 industrial units are collected. The data are used to estimate CO_2 emissions at the facility level, where the used emission factors are calculated based on the type of industry, fuel, efficiency, and productivity. The adopted calculation methodologies closely follow the IPCC guidelines, where possible. We then characterized CO_2 emissions by their industrial category, rates, and geographical location.

In this work, we make publicly available for the first time an inventory of CO_2 emissions from stationary sources in KSA in a partial open-access database. This database will be beneficial for the public, researchers, and agencies interested in understanding the GHG footprint map in KSA and assessing the potential of CO_2 capture, transportation, utilization, and storage. This work is organized as follows: first, review the reported cumulative CO_2 emissions across KSA from various national and international agencies. Then introduce the calculation methods, followed by a detailed assessment of the six major industries, including electricity, desalination, hydrocarbon refining, cement production, petrochemical, and iron & steel industries. An evaluation of the emitted CO_2 concentrations across the different emitters is then presented, followed by discussions and conclusions.

2. Methodology of estimation CO_2 emissions for KSA

The 2006-IPCC guidelines recommend three methodologies to estimate emissions from stationary combustion units, referred to as Tier 1, 2, and 3 [20]. Tier 1 is the simplest method, where emissions from fossil fuel combustion are calculated using default emission factors based on the fuel type. In Tier 2, the emission factors are country- and fuel-specific. Tier 3, however, is the most rigorous and data-demanding method, where the emission factors are fuel- and technology-specific and require detailed data at the facility level when available. UNFCCC emission inventories are typically based on Tier 2 and Tier 3, while Tier 1 is commonly used by international environmental agencies to estimate world CO_2 emissions from fossil fuel combustion by country. In Tier 1, the standard emission factors based on the average carbon content of crude oil and natural gas are, respectively, 3.07 and 2.35 tons of CO_2 per one ton of oil equivalent. Due to discrepancies in the available input data, the calculation methods, and the country-specific parameters, inventory estimates in a country may vary by 10 % on average but sometimes may vary by as much as 50 % [9].

In Fig. 1, we show CO_2 emission estimates for KSA by four international agencies, including EIA [21], EDGAR [48], CDIAC [13], BP [16], and the Saudi DNA [3]. Note that there is some variability in the estimates corresponding to an average standard deviation of around 12 $MtCO_2$ per year. This discrepancy in the estimates may be related to the different calculation methods employed and uncertainty in the input data. The estimates of the international agencies are based on Tier 1 and 2, whereas the DNA estimates are based on Tier 3, which are expected to be more rigorous in terms of input data quality (where Tier 1, 2, and 3 are defined in the previous section). Nonetheless, all trends show reasonable consistency in terms of emission trends. The average of all the estimates, shown by the dashed line in Fig. 1, suggests an annual increase in CO_2 emissions of about 3.7 % per year between 2005 and 2015 followed by a decreasing growth trend, which is attributed to different factors [6,25].

According to the Saudi DNA, the total emitted mass of CO_2 during 2016 was approx. 602 million metric tons per year (mty). The

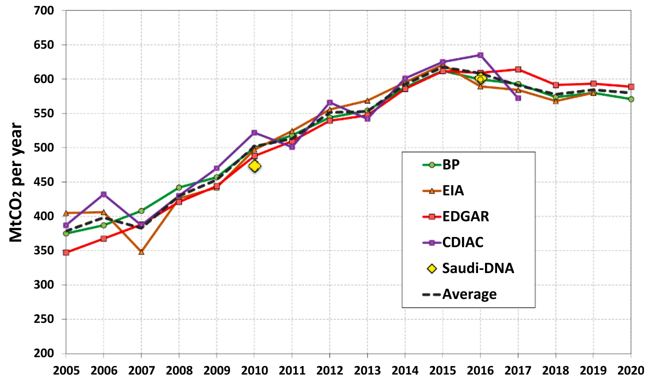

Fig. 1. CO_2 emission estimates in a million metric tons per year from different international agencies and the Saudi DNA; the dashed line shows the average trend.

contributions of the emitting sectors are shown in Fig. 2. The cumulative contribution of the top six energy and industry sectors, including electricity, desalination, petroleum refining, petrochemicals, cement, and iron & steel, is around 77 % of total emissions (Fig. 2). This work provides a detailed map of the stationary CO_2 sources associated with the top six emitting sectors.

3. Carbon-emission calculations

Carbon emission calculations have different levels of reliability and complexity, depending on the available input data. Data were collected at the facility level from more than 1200 units covering more than 190 distinct locations, which account for almost all primary emitting stationary sources covering the six industrial sectors mentioned previously. The database contains data records describing the industrial sector type, location, fuel type, combustion technology, unit age, and annual production rates. It also considered the units that have been recently phased out. No complete records were available on the volumes of the consumed fuels for each facility. Thus, emissions are calculated from the production rates and their corresponding emission factors; the latter is based on the industry type, fuel type, and combustion technology. The last publicly reported total emissions for KSA per sector as per DNA Document [3] covers 2016 emissions. In this work, Total CO_2 Emissions for the Kingdom were estimated, covering emissions as of the year 2020, based on various public data (details about data sources will be given in later sections).

In comparison with DNA's reported emissions for 2016, our calculated estimation for 2020 showed a slight decrease of 2.5 % in total CO_2 emissions from 437 mty to 426 mty, as shown in Fig. 3. This change is mainly due to a reduction in desalination and refinery emissions due to the low demand during the COVID-19 pandemic, and other factors [6,25]. Note that in Fig. 3, we show the combined and separate emissions for the electricity and desalination sectors to avoid confusion in allocating emissions for some desalination plants that serve a dual purpose of electricity generation and water desalination. Fig. 4 displays our calculated bubble map showing the locations and emission intensities from the different industrial sites across KSA. The following sections provide detailed descriptions of the calculation methods for each industrial sector.

4. Emissions from the electricity sector

The electricity sector is the largest consumer of domestic oil and gas in KSA, where electricity generation is growing at an annual rate of around 6.3 % [1,15]. This growth in electricity consumption is expected to continue [45,54,55]. According to the Saudi Electricity Company (*SEC*), the residential sector consumes about 50 % of total electricity production, while the rest is divided almost equally between the industrial sector, commercial sector, and governmental agencies [60]. More than 80 power plants have more than 900 units across the country, with capacities ranging from small units (24 MW) to much larger units, such as the Shuaiba plant (6800 MW). The majority of the power plants are located in the central province (Riyadh), the eastern region (Dammam, Ahsa, and Jubail), and the western region (Macca, Jeddah, and Madinah). The age of those units ranges from very recent to more than five decades old. Many facilities, around two 200 units, have been phased out in the last couple of years and replaced with new, more efficient ones. Based on 2020 data gathered from ECRA Saudi Arabia Electrical company annual report, the total fuel contribution to electricity generation from natural gas, crude oil, heavy fuel oil (HFO), and diesel was, respectively, 41.3 %, 22.3 %, 28.2 %, and 8.1 %, as shown in Fig. 5 (left). The technology used in electricity generation ranges from high-efficiency combined cycle units (11.7 %), single-cycle gas turbines (42.5 %), steam turbines (45.3 %), and diesel generators (0.5 %), Fig. 5 (right). The overall efficiency of electricity generation is around 32 % [61]. The distribution of the primary fuel used in power plants is shown in the bubble map in Fig. 6, where the bubble size is proportional to the production capacity. Natural gas usage is concentrated in the eastern

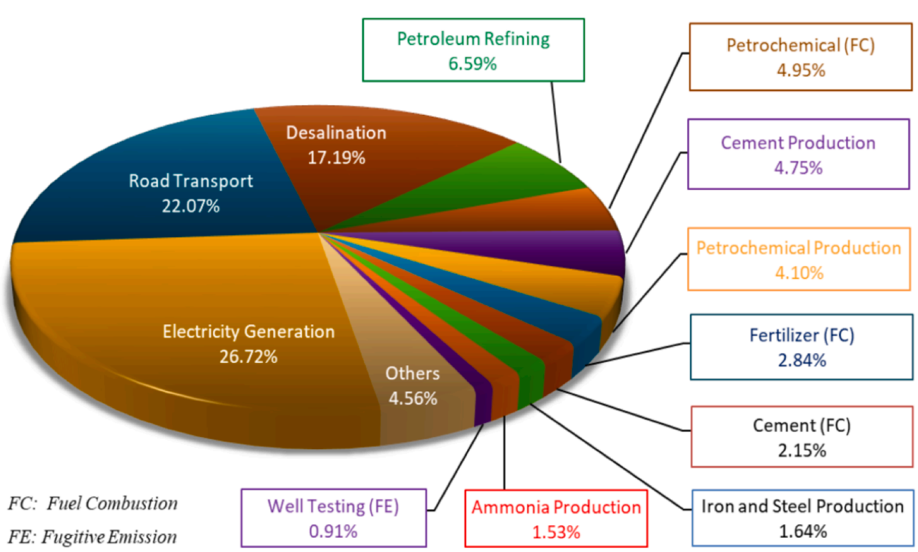

Fig. 2. Saudi DNA reported the relative contributions of major CO_2 emission sources in KSA in 2016 [3].

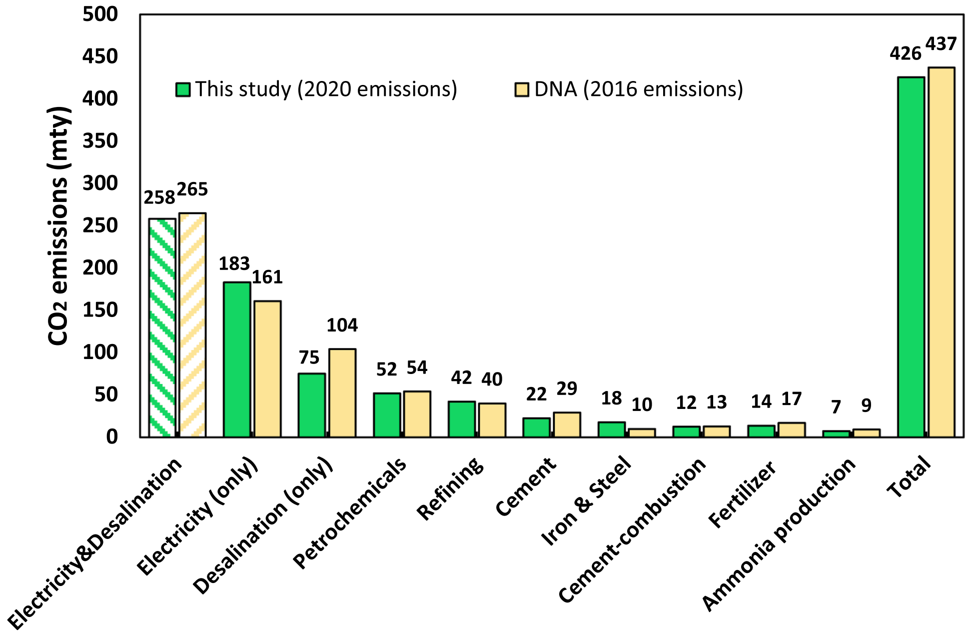

Fig. 3. Calculated CO_2 emissions from this study based on 2020 data, compared to reported DNA estimates for 2016 [3]. Note that we show the separate and combined emissions for the electricity and desalination sectors to avoid confusion in allocating emissions to dual-purpose electricity and desalination plants.

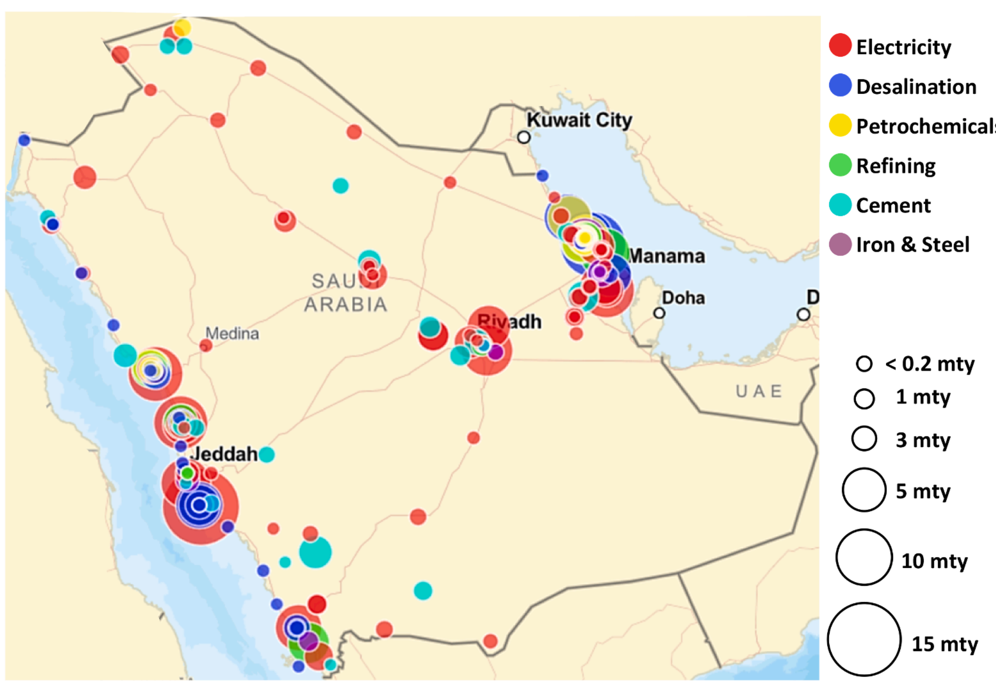

Fig. 4. Bubble map showing the distribution and intensity of our calculated CO_2 emissions for 2020 from the six major industrial sectors in KSA.

region close to hydrocarbon reservoirs, whereas liquid hydrocarbon usage is more evenly spread elsewhere in the country.

Emissions intensity is not homogeneous across the different power plants; it varies depending on several factors, including combustion technology, efficiency, and the fuel type [57,69]. As shown in Fig. 5, the primary technologies are based on Gas Turbines (GT), Steam Turbines (ST), and Combined Cycle (CC). In the case of CC, fueled by crude oil or natural gas, heat is recovered from the combustion turbine exhaust gas to produce steam that powers a secondary turbine, resulting in higher overall efficiency and, therefore, a lower CO_2 emission per kWh. A typical emission rate is within 0.37–0.48 kg CO_2 per kWh [26]. On the other hand, GT and ST exploit a single cycle resulting in lower efficiency and, consequently, higher CO_2 emission factors ranging from 0.54 to 0.76 kg CO_2 per kWh [46]. The applied CO_2 emission factors based on the technology and the fuel types are provided in Table 1 [64]. Fig. 7 shows the total electricity generation and the corresponding calculated CO2 emissions versus time between 1986 and 2020. In 2010, our calculated CO_2 emissions were about 135 mty, slightly lower than the 147 (mty) reported in the Saudi DNA document. As of 2020, our database accounted for a cumulative electricity generation of about 332 terawatt-hours (TWh). Among those, 282 TWh are generated in stand-alone power plants, while the rest are generated in desalination

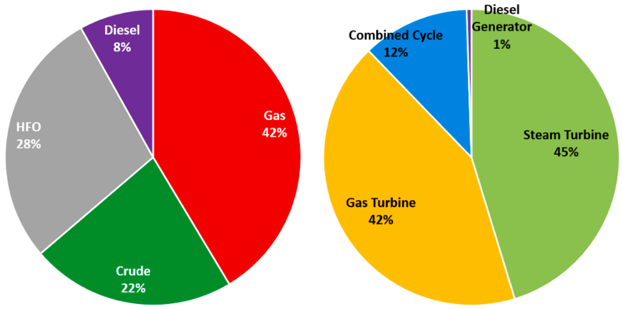

Fig. 5. Relative contributions of fuels (left) and technology type (right) used for electricity generation in 2020.

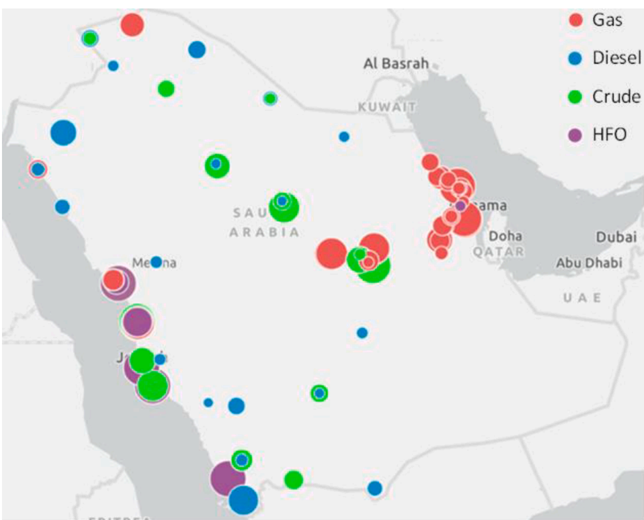

Fig. 6. Distribution of the primary fuels used in electricity generation in 2020; bubble sizes are proportional to the production capacities.

Table 1
CO_2 emission factors of various power generation units combusting different fuel types.

Fuel	Combustion technology	CO_2 emission factor (kg CO_2/kWh)
Crude	gas-turbine	0.76
	combined-cycle	0.48
	steam-turbine	0.67
Diesel	gas-turbine	0.76
	diesel-generator	0.76
Gas	gas-turbine	0.54
	combined-cycle	0.37
	steam-turbine	0.58

industries. The 282 TWh generated by power plants corresponding to CO_2 emissions of 183 mty; this number was around 5 % higher in 2016 electricity with a larger production. Thus, the resulting average emission rate is about 0.65 kgCO_2 per kWh, consistent with a study performed by the Saudi DNA. Recently, ECRA started to publish data about the amount and type of fuel needed in the electricity sector; in the 2019 annual report 1486, 548, 613, and 119 trillion BTUs of natural gas, crude oil, HFO, and diesel were consumed, respectively. The amount of fuel consumed corresponds to around 178 mty, less than 4 % of our calculated 183 mty emissions based on production, fuel, and technology. Fig. 8 shows our calculated time-lapse heat maps for CO_2 emissions from power plants over the last two decades. The CO_2-emission bubble maps corresponding to the distribution of power plants in the country are shown in Fig. 9 (left), while Fig. 9 (right) shows the emission rates per

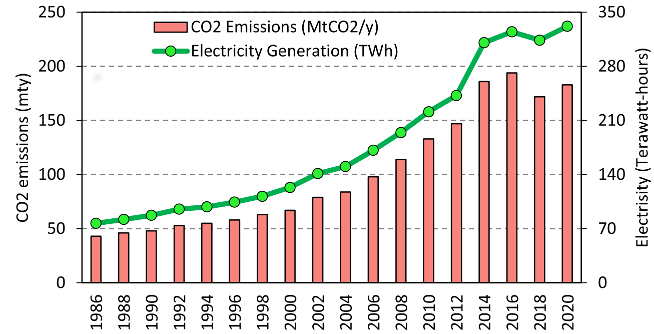

Fig. 7. Electricity generation and corresponding CO_2 emissions during 1986–2020.

region. The CO_2-emitting power plants are primarily concentrated in the central, eastern, and western regions.

5. Emissions from the desalination sector

With a desalination rate of around 7.6 million cubic meters per day, KSA is the world's largest producer of desalinated water [34,41]. The desalination and electricity sectors account for about 40 % of the total energy consumption in KSA [32]. The dominating desert environment with scarce precipitation imposes the country's dependence on non-renewable freshwater subsurface aquifers and energy-intensive water desalination plants. The agricultural sector consumes more than 84 % of the total national demand for freshwater [47,67]. On the other hand, drinking water consumption increases dramatically, with an annual growth rate of about 8 % [31]. This high-water demand is driven by the growing population, changing lifestyles, and the country's industrial development. About 30 major desalination plants are distributed along the Red Sea and the Arabian Gulf coasts (Fig. 10), which account for 18 % of desalinated water worldwide, and 43 % of the GCC capacity [59]. The state-owned Saline Water Conversion Corporation (SWCC) is the largest desalinated water producer in the country. In 2019, desalinated-water production was around 7.6 million m3 per day, with 56 % (or 4.3 million m3 per day) from SWCC and the rest from eleven companies in the private sector [68]. Three desalination technologies are predominant see (Fig. 11), left: multi-stage flash distillation (MSF), reverse osmosis (RO), and multi-effect distillation (MED), corresponding, respectively, to 57.7 %, 29.0 %, and 13.1 % of the total installed capacity [59].

Desalination is an energy-intensive process with a potentially significant environmental footprint that affects marine life and air quality [17,51]. The energy requirement and environmental impact vary depending on the technology and the fuel used [53,76].

The MSF and MED units are usually integrated with electricity generation, while RO uses the electric energy provided by an adjacent power plant or through the grid [22]. This direct and indirect use of fossil fuel results in significant GHG emissions, placing desalination as the second top stationary emitting sector after electricity generation in KSA. We estimated the volumes of CO_2 released from each desalination plant based on the desalinated water volume and the adopted technology [24]. The CO_2-emission factors are relatively high, owing to the high salinity of the Red Sea [41]. We also considered the dual-purpose plants that provide freshwater as the main product and electricity as a by-product. According to the DNA report, desalination plants emitted around 104 mty in 2016 [3].

Additionally, 50.8 TWh of excess electricity was exported, corresponding to about 27.3 mty of CO_2. The excess electricity export is about 23.8 TWh by SWCC and 27.0 TWh by the private sector. By excluding the emissions related to the excess electricity, we estimate that the average apparent emission factor of desalination in 2019 improved to become around 15.2 kgCO_2 per m^3 of desalinated water from 21.4 kg

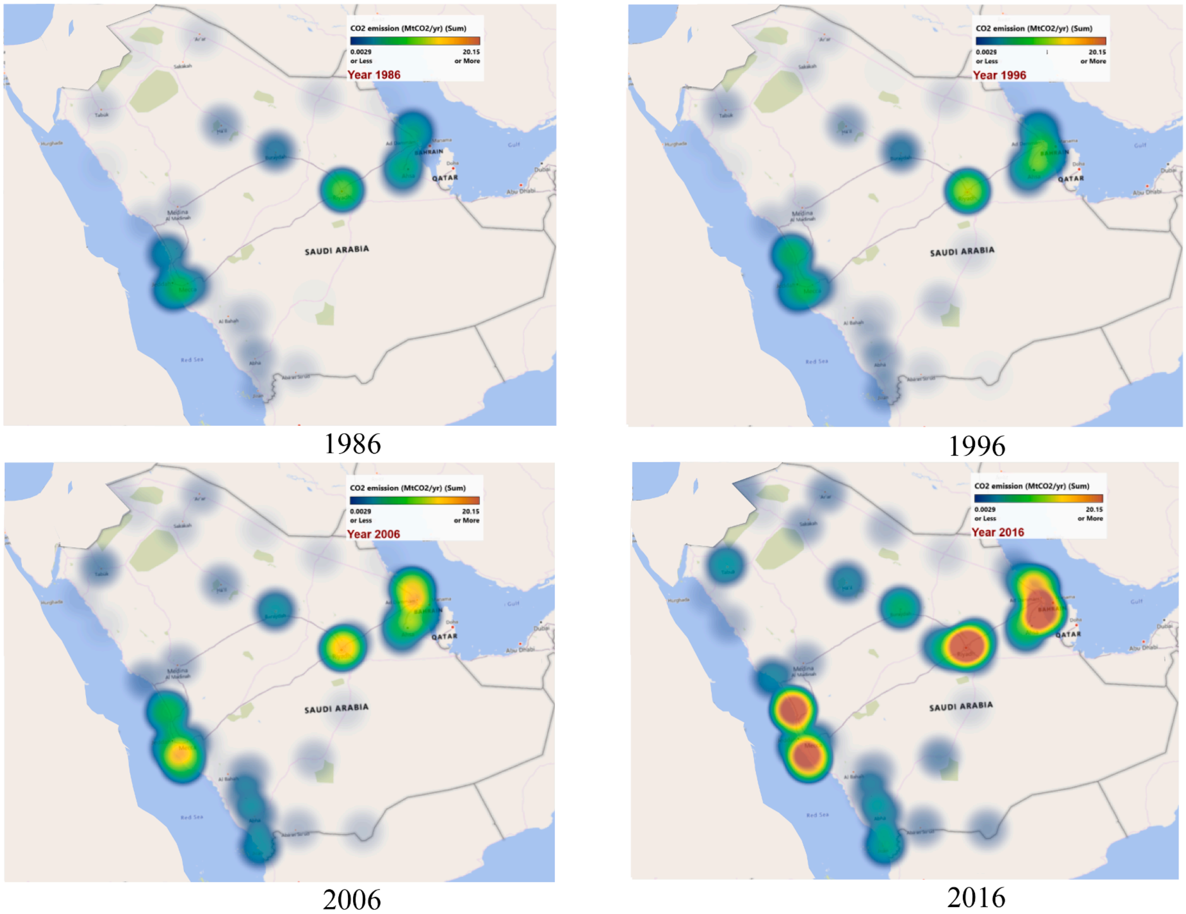

Fig. 8. Heat maps showing the evolution of CO_2 emissions from electricity generation between 1986 and 2016.

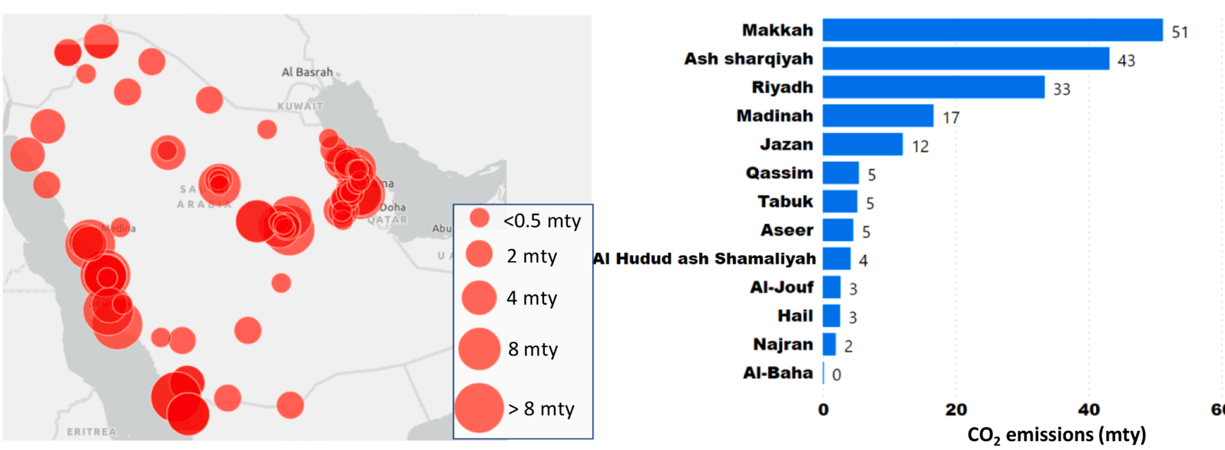

Fig. 9. Map of power plant locations with corresponding calculated emissions (million tons per year (mty)) in 2020, and cumulative emissions per region.

CO_2 per m3 in 2016. Since 2010, desalination named-capacity has increased by about 52 %. Based on 2019 estimates, the corresponding CO_2 emissions from this sector, including excess electricity generation contribution, have increased dramatically to 73mty. The emissions from water desalination are estimated based on the emission factors related to the technology of the different units, as shown in Table 2. The contribution of each technology to total emissions is shown in Fig. 11 (right). The emission bubble map from all desalination plants is shown in Fig. 12 (right), where emissions appear to be evenly distributed between the Arabian Gulf coast (Eastern region) and the Red Sea Coast (Macca, Medinah, Jazan, and Tabuk), as shown in Fig. 12 (left).

On the other hand, ECRA reported the amount and type of fuel consumed in the desalinated sector. According to its 2019 annual report, ECRA stated that desalination consumed 755, 244, 195, and 7 trillion BTUs of natural gas, crude oil, HFO, and diesel. Thus, the amount of fuel consumed corresponds to a carbon dioxide emission of 74.7 (mty), which is 97 % compatible with the emission data calculated from production activities in the desalination sector.

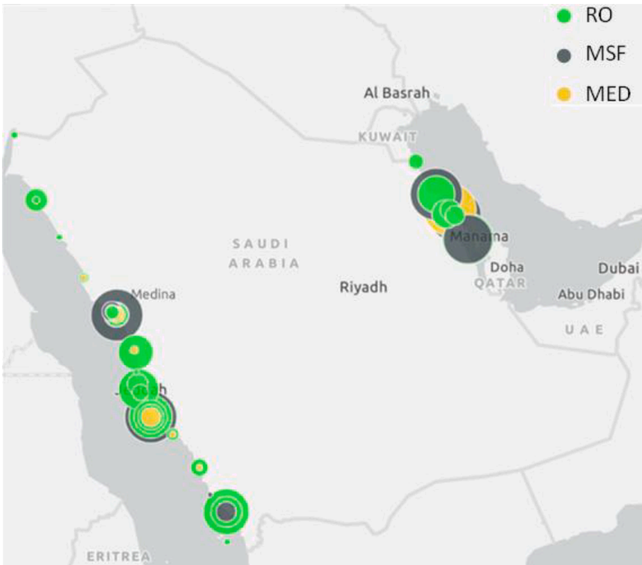

Fig. 10. Bubble map showing the locations of the desalination plants and the adopted technologies, with bubble sizes relative to the production capacities in 2020.

6. Emissions from the refining sector

Besides being a leading producer of crude oil globally, KSA transforms part of its crude oil into a multitude of refined products, such as gasoline, diesel, HFO, and lubricants, among others. The refining sector is mainly managed by Saudi Aramco either solely or through joint ventures with other companies such as TOTAL, Shell, Exxon Mobil, and others. In the last few years, as shown in Fig. 13 (left), an increase in its refining capacity and throughput was achieved, placing KSA within the world's top ten oil refining countries [16,63]. There are eight operating refineries located in Jubail, Ras Tanura, Riyadh, Yanbu, and Rabigh, with a total named capacity of around 2.8 million barrels daily (mbd) and a throughput of about 2.6 mbd. As of 2020, a 6.1 % decrease compared to the previous year was due to a lowering in demand as a consequence of the pandemic. Fig. 13 (right) shows the cumulative throughput share of all refineries in KSA, collected from data for 2016. Recently, a small refinery in Jeddah of capacity 80,000 BPD was permanently shut down by Aramco for environmental and age concerns.

In petroleum refineries, GHG emissions are mostly generated from fuel combustion-related sources, such as process heaters, steam boilers, and process furnaces, and other processing units, such as fluid catalytic cracking, hydrogen production, and sulfur recovery, among many others. Emissions from a refinery are mostly from combustion and catalytic cracking, which depend on the crude API gravity (which refers to American Petroleum Institute gravity indicating how heavy or light a liquid crude is compared to water), the type of the refinery, and the sulfur content [28]. In this work, due to the absence of combustion data, we estimate the emissions based on two factors: the production throughput of the refineries and the type of processed crude. Our calculations do not include CO_2 emissions related to oil extraction and transportation. In a recent study [43] that evaluated the Carbon Intensity (CI) of oil-producing countries worldwide, Saudi Arabia was ranked second after Denmark with the lowest CI. The CI is a measure of carbon emissions related to upstream and midstream activities, including exploration, production, separation, re-injection, flaring, and transportation to the refinery inlet. With low gas flaring and water-cut per produced barrel of oil, the CI in KSA is around 4.6 gCO2/MJ, corresponding to 27 kg of CO_2 per one produced barrel of oil, which is significantly lower than the world CI average of 10.3 g CO_2/MJ. The types of crude oils produced in KSA are Arabian heavy, medium light, extra light, and super light oils. The emission factors (EF) and other properties of Arabian oils are provided in.

Table 3 [33,42]. Our calculated CO_2 emissions based on the emissions factors and the refinery throughputs from the operational oil refineries sum up to 49 mty, and are shown in Fig. 14. As for 2020 before the Jazan refinery was set to operations, the CO_2 emissions from refineries was about 42 mty. Fig. 14, on the left, shows the regrouped emission rates by city, and Fig. 14, on the right, shows the refinery locations and the corresponding emissions. As mentioned previously, the refinery in Jeddah has been decommissioned.

7. Emissions from the cement and iron & steel sectors

Saudi Arabia hosts the largest construction industry in the Gulf region, including cement and iron & steel markets, driven by major capital projects at the planning and execution stage [18]. Rich deposits of limestone, the primary raw material of cement, and relatively low energy costs provide ideal conditions for cement production in KSA. Cement production involves transforming limestone into clinker using high heating temperatures, followed by clinker grinding and mixing with other binding additives to form the cement. Around fifteen cement companies are distributed among more than 20 locations across the country, with a total capacity above 70 million metric tons (MT) of clinker production per year [35]. Within the last decade, clinker production peaked in 2015 at around 58 MT, as shown in Fig. 15 (left) [7,10]. Since 2015, clinker production dropped to about 49 MT per year, a decline of about 17 %. In Fig. 15 (right), we show the cumulative clinker production in 2015 distributed by city, where Riyadh is the leading producer.

Table 2
CO_2 emission factors for different types of desalination technologies.

Technology	CO_2 emission factor (kg CO_2/m^3)
MSF	23.4
MED	18
RO	3.4

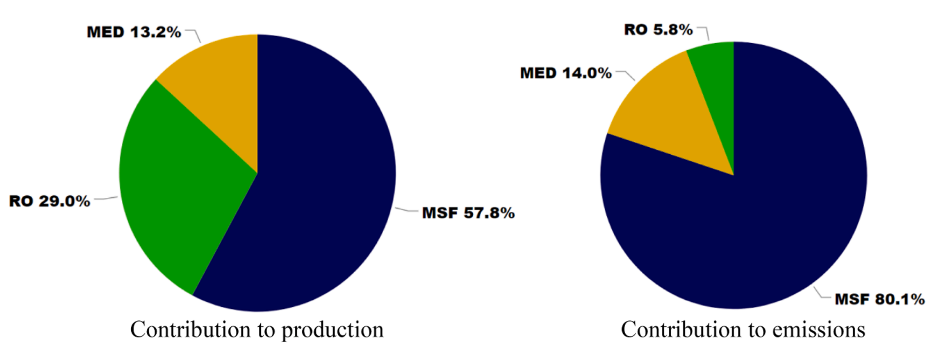

Fig. 11. Contribution of the MED, RO, and MSF technologies to desalination production (left), and to CO_2 emissions (right).

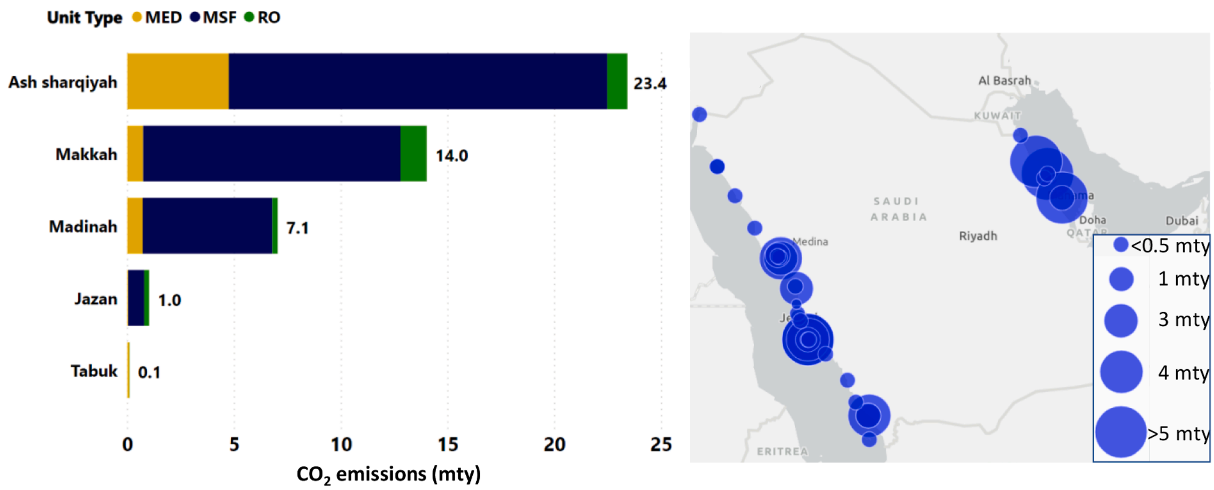

Fig. 12. Annual CO_2 emissions (mty) from desalination plants in different regions combined with the contribution of the technology used (left), and bubble map showing the locations of the desalination plants and their relative CO_2 emissions in 2020.

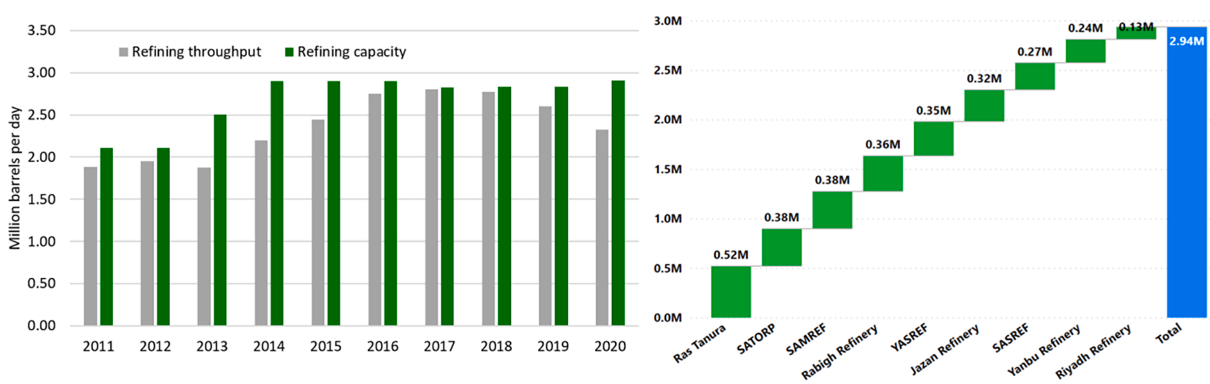

Fig. 13. Total oil refining capacity and throughput (left) from 2011 to 2020, and cumulative throughput share by refinery in 2016 (right); Jeddah's refinery is currently shut down permanently.

Table 3
Information about the different types of crude in KSA and an average CO_2 emission factor for refining each type.

Marketable crude type	API	Sulfur (wt.%)	EF (kg CO_2/barrel)
Arab heavy	28	2.8	47.1
Arab medium	31	2.4	43.3
Arab light	33	1.8	40.2
Arab extra light	38	1.1	37.8

The iron & steel sector is another vital industrial sector that is crucial to the Saudi economy. Steel demand in KSA is around 10–12 million metric tons (MT) per year, while the current production capacity from local companies is about 8 MT. Like the cement industry, the iron & steel industry has significantly grown due to high demand in the construction sector. The production rate of crude steel and reduced direct iron over the last decade is shown in Fig. 16 (left) [75]. The production trend of iron & steel peaked around 2014, showing a similar trend to cement production, as shown in Fig. 16 (right).

Cement is composed of more than 90 % clinker and small amounts of other binding additives such as gypsum. Clinker production is the primary source of CO_2 emissions, which are emitted from two sources. The first source is from the chemical processes, and the latter is related to the fuel combustion needed in the manufacturing process. During clinker production, carbon dioxide is released as a by-product of the transformation of calcium carbonate (CaCO3; the main constituent of limestone) into calcium oxide (CaO). This calcination process occurs at high temperatures, ranging from 600 to 900 °C. The formed CaO is then reacted with other minerals to produce the clinker. To estimate CO_2 emissions from clinker production, the IPCC guidelines provide a general methodology based on multiplying the amount of the produced clinker by an emission factor. The emission factor depends on the lime concentration in the clinker. In this work, we used the IPCC Tier 1 method, which recommends using an emission factor of 0.507 tons of CO_2 for one ton of clinker. This default emission factor corresponds to a lime concentration of 64.6 %. Accordingly, we collected data on clinker production during 2019 from different cement plants in KSA, as shown in Fig. 15 (right). The corresponding direct CO_2 emissions add up to about 22.5 mty of CO_2, decreasing from 29.3 mty of CO_2 in 2015. The reduction in the emission is due to lower demand for cement in the Kingdom as major construction projects announced by the government proves slow to get off the ground, in addition to the demolishing of some old production lines by some factories, as in the case of Yanbu and Yamama cement factories aiming to improve their efficiency. Fig. 17 (right) shows a bubble map of emissions and plant locations, while Fig. 17 (left) shows the cumulative emission share by city; as expected, Riyadh has the highest emissions. Similarly, we followed the Tier 2 method in the IPCC guidelines to estimate emissions from iron & steel. Fig. 18 (left) shows the cumulative CO_2 emissions ranked by city, where Jubail and Dammam have the highest emissions, and (right) shows the distribution of iron & steel plants and their corresponding emissions.

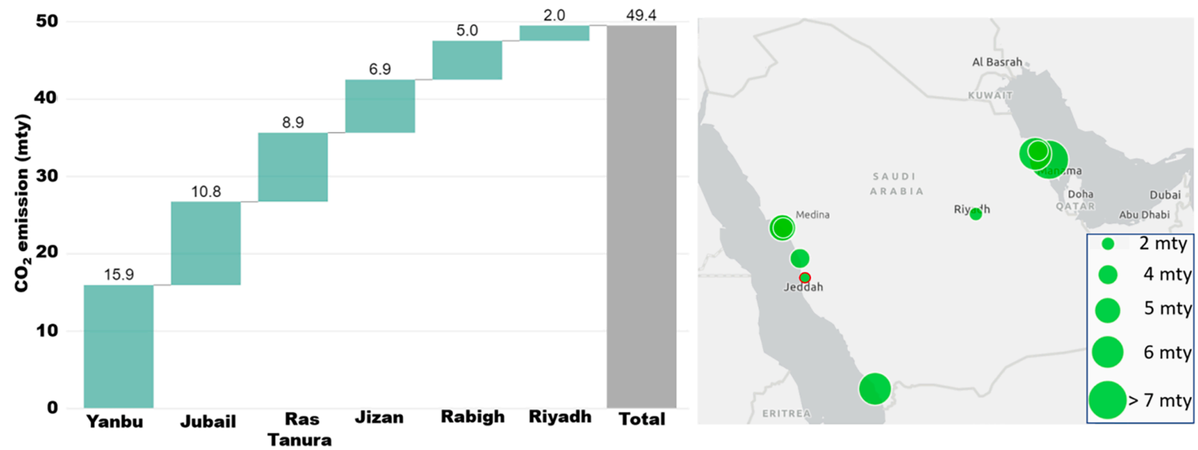

Fig. 14. CO_2 emissions by city from refineries (left) in 2020, and bubble map showing refinery locations and corresponding emissions (right). Note that Jeddah's refinery (highlighted in red) was permanently shut down in 2017.

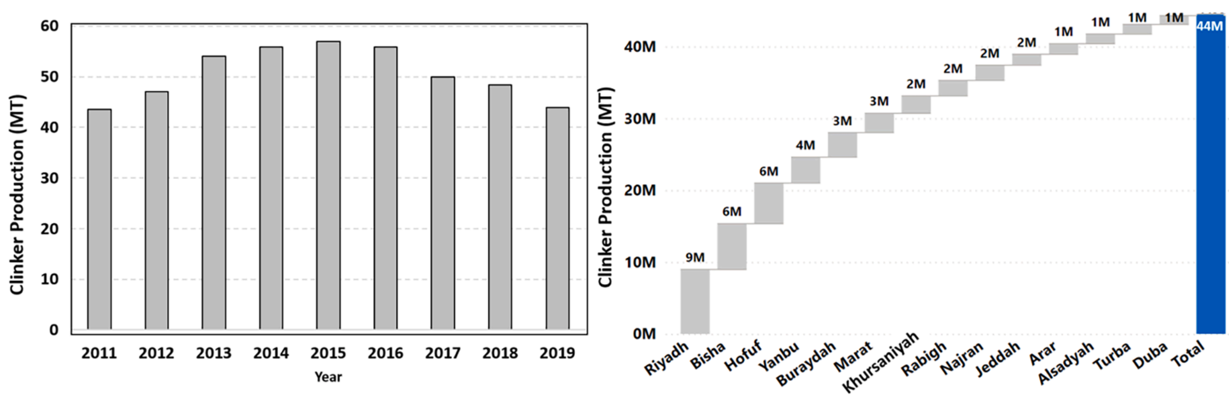

Fig. 15. Total clinker production (left) from 2011 to 2019, and cumulative production share by city for 2015 (right).

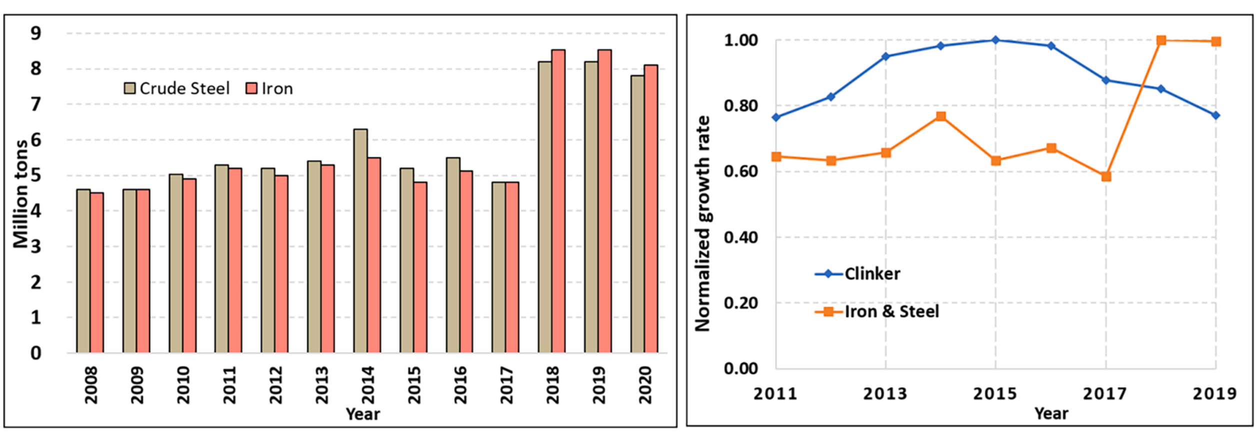

Fig. 16. Total crude steel and direct reduced iron productions (left) from 2008 to 2020, and comparative sector growth trends for clinker and iron & steel (right).

8. Emissions from the petrochemical sector

The petrochemical sector is an essential driver of the Saudi economy and is the biggest non-oil export in KSA. Petrochemical production and exports are expected to keep growing in the coming years, in line with the Saudi [40] strategy [62]. The development of this sector began in the 1980s when the government developed the facilities and infrastructure to eliminate gas flaring during crude oil production. The so-called "Master Gas System" is designed to process and transport produced gas from hydrocarbon fields in the eastern region and pump it to the two principal petrochemical cities, Yanbu and Jubail. Within the last decade, this sector has undergone significant expansion, almost doubling the petrochemical capacity, driven by high demand and investments [30]. The sources of the petrochemical feedstock are mainly derived from ethane, liquefied petroleum gas (LPG), methane, and, to a lesser extent, naphtha, a by-product of oil refining. The associated gas provides both ethane and methane, while LPG provides propane and butane. The heavy usage of ethane and LPG leads to the domination of olefin and

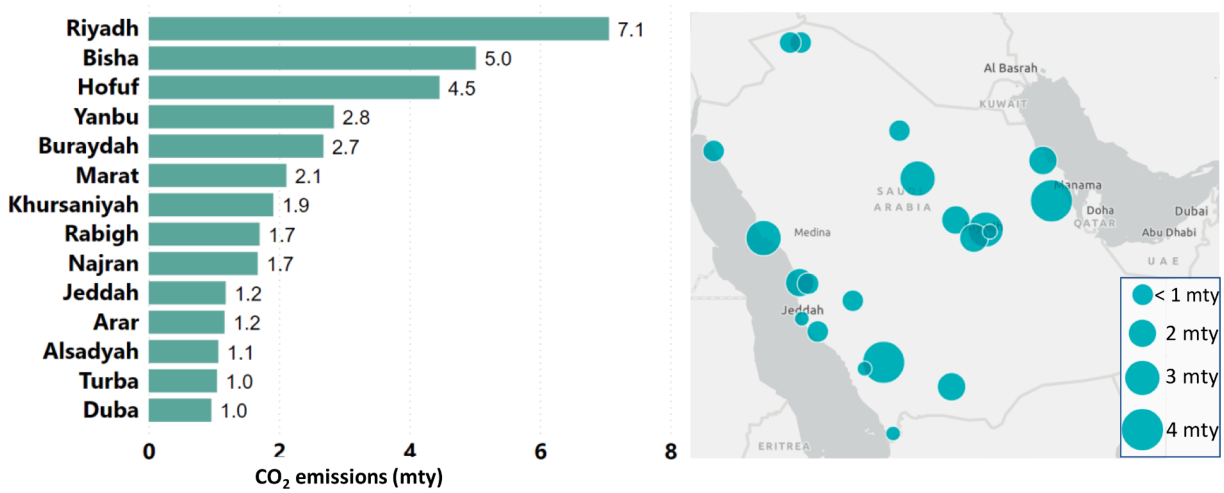

Fig. 17. CO_2 emissions from cement production per city (left), and bubble map showing plant locations and corresponding emissions (right) in 2020.

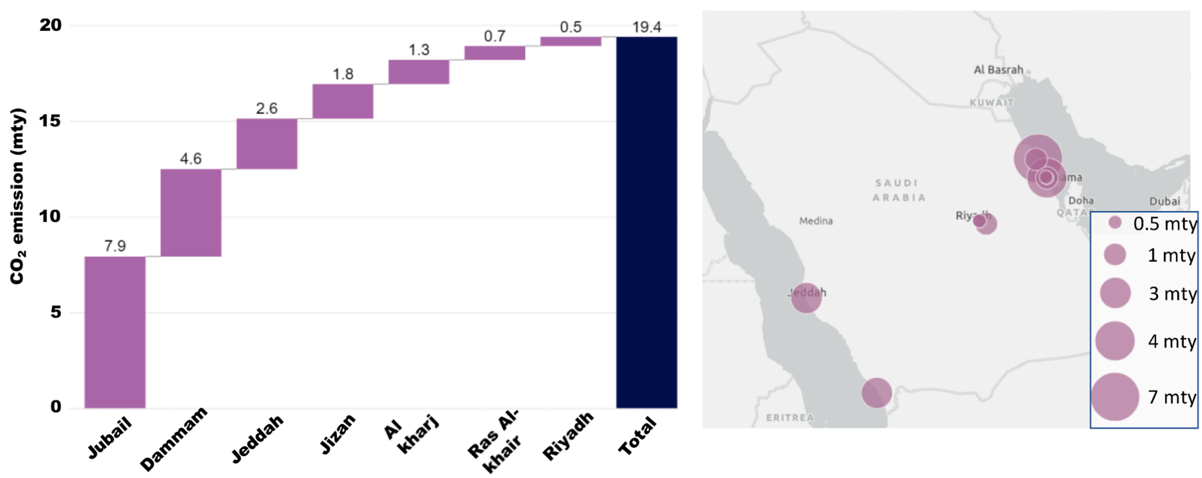

Fig. 18. CO_2 emissions from iron & steel productions per city (left), and bubble map showing plant locations and corresponding emissions (right) in 2020.

alcohol production, such as methanol, ethylene, propylene, and butylene, which represent 75 % of total production capacity. On the other hand, aromatics are produced from naphtha and account for about 13 % of the total capacity in 2016 [30]. These primary petrochemicals are then utilized to produce a wide range of other chemicals (Table 4).

The associated emissions from the petrochemical sector are generated from three main sources: 1) fuel combustion used to heat the steam-cracking furnace, 2) electricity consumption, and 3) feedstock. Processing the primary petrochemicals is energy-intensive. Such processes include steam cracking, oxidation, syn-gas production ($CO + H_2$), reforming, and electrochemical processes, among others. To estimate CO_2 emissions, we followed the Tier 1 method, described in the 2006 IPCC guidelines, based on default emission factors. KSA produces more than 50 petrochemical products, of which one-third comprise more than 85 % of the total capacity, corresponding to 86.4 MT per annum [2]. Here, we focus on the leading 16 products, shown in Fig. 19, which are the primary and intermediate petrochemicals distributed over more than 45 industries, mostly located in Jubail and Yanbu, some in Rabigh, Dammam, and Ras Alkhair.

Table 4
Emissions factors applied for the different chemical products.

Chemical	Emission factor (kg CO_2/kg)
Ethylene	0.88
Methanol	0.28
Polyethylene	0.53
Propylene	0.85
Mono Ethylene Glycol (MEG)	0.38
Sulphuric acid	0.14
Polypropylene	0.20
Ammonia	1.59
Urea	−0.46
Diammonium Phosphate (DAP)	0.86
Methyl Tertiary Butyl Ether (MTBE)	0.80
Styrene	0.37
Phosphoric acid	1.45
Lubricant Oil	1.07
Benzene	1.76
Ethylene dichloride	0.19

We collected information on the capacity and production of the different chemicals from a wide range of public resources. The emission factors depend on the energy requirement and feedstock type [12,74]. For example, the production of ethylene from ethane or naphtha could raise the emission factor from 0.88 to 1.3 $kgCO_2/kg$ (per one kg of product). Moreover, changing the fuel used can impact the emission factor; for instance, producing ethylene from natural gas will emit 0.88 $kgCO_2/kg$, whereas using fuel oil will emit 1.2 $kgCO_2/kg$ [66]. In Table 4, we summarize the emission factors we applied for the main produced chemicals [66,73]. CO_2 emissions from chemical productions distributed in each city and by the three chemical types (petrochemicals,

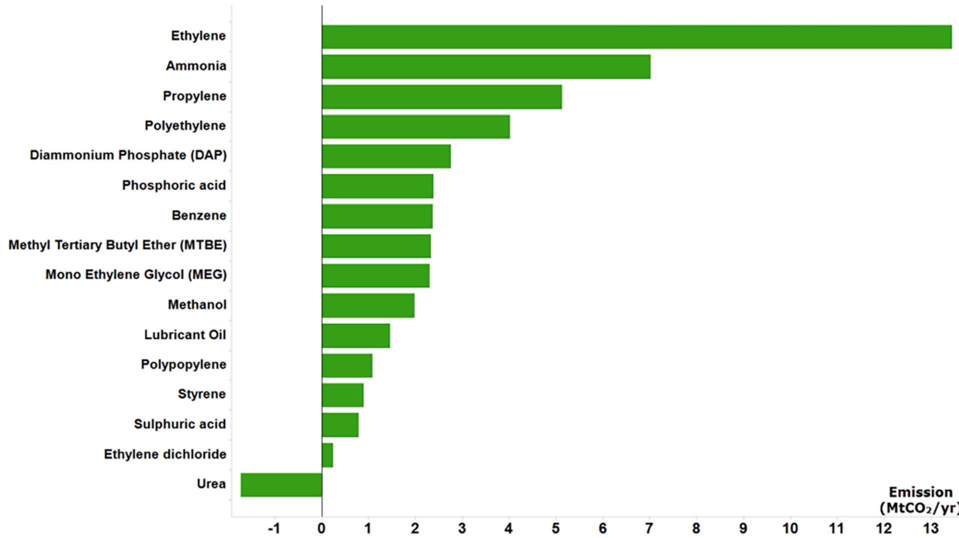

Fig. 19. Primary and intermediate chemicals produced in 2015 and their corresponding CO_2 emissions.

fertilizers, and ammonia) are shown in Fig. 20 (left), with cumulative emissions by type of 42.1, 13.7, and 5.7 mty, respectively.

9. CO_2 concentration in the flue gas

It is important to localize CO_2 emission sources with their rates and concentrations. This information is crucial to estimate the economic aspect of carbon capture, compression, and transportation. The concentration of CO_2 in the flue gas is a primary factor impacting the capturing cost, which often represents the highest cost of a CCUS project. For instance, capturing CO_2 from natural gas processing units, fertilizer, and hydrogen production is cheaper than capturing it from natural gas combined cycle power plants. Those highly concentrated sources with CO_2 would be more attractive for capturing. CO_2 concentrations in the flue gas are estimated based on reported values in the literature, which are a function of the industry, combustion technology, and the fuel used. For example, in a cement plant (kiln off gas), the CO_2 concentration by volume ranges between 14 % and 33 %, while in an open cycle natural gas-fueled gas turbine, it is in the range of 4 % to 7 %. Table 5 shows the used concentration ranges corresponding to the different industries and combustion technologies, which provide low, high, and average values. The average values are used to quantify the volumes of CO_2 emitted at different concentration ranges. Fig. 21 shows the map of emitters corresponding to CO_2 volume concentrations above 15 %. The contributing industries correspond to ammonia production, hydrogen production, cement kiln off gas, and integrated steel mills. While the emitters with CO_2 concentrations less than 15 % in the flue gas are mainly electricity, desalination, and the majority of the petrochemical sector. We found that about 60mty of CO_2 is emitted with a concentration that exceeds 15 % in the flue gas, while the majority of the

Table 5
Literature-based carbon dioxide percent in the flue gas for different units and sectors.

Technology	low	mid	high
Natural gas-fired boilers/steam	7	8	10
Natural gas Gas turbines CC	3	5	7
Oil-fired boilers/steam	11	12	13
Natural gas Gas turbines	4	5	7
Oil Gas Turbine	11	12	13
Oil combined cycle	11	12	13
Desalination RO	8	12	13
Diesel Generator	8	10	12
Refineries	4	8	16
Blast furnace gas/integrated steel mills	15	20	27
Cement kiln off gas	14	20	33
Petrochemicals	7	8	9
Ammonia production	17	18	19
Ethylene oxide	7	8	9
Hydrogen production	15	18	20
Methanol production	9	10	11

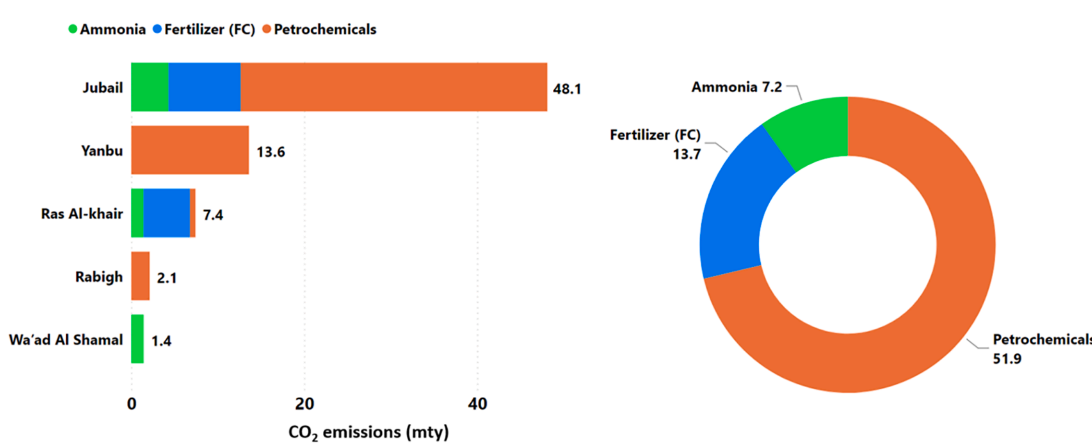

Fig. 20. CO_2 emissions from petrochemical, fertilizer, and ammonia production by city (left) and the cumulative emissions from each chemical type (right).

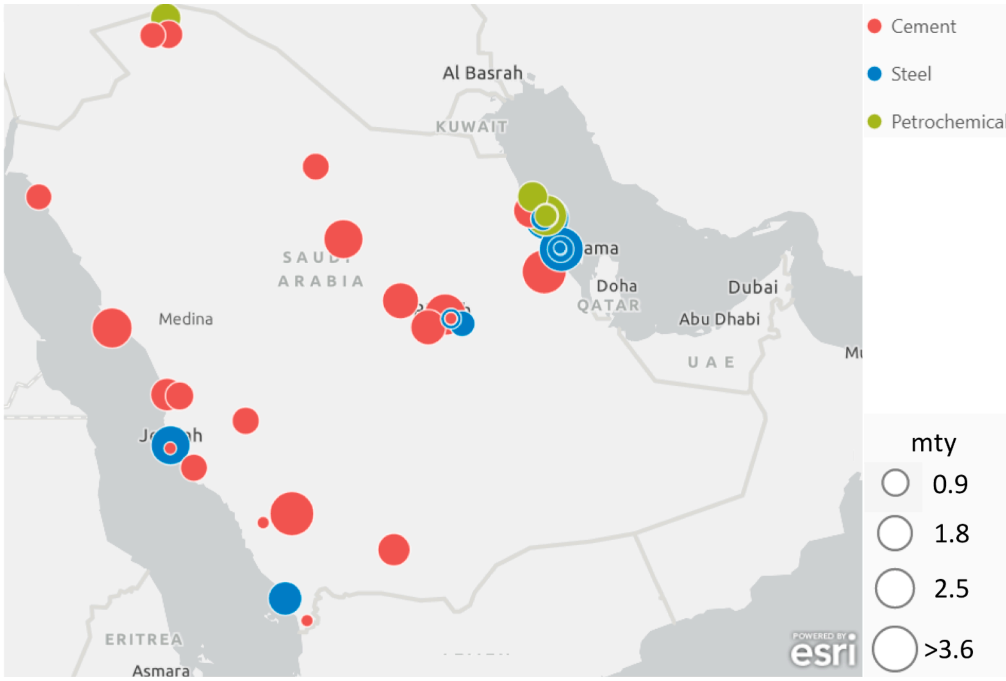

Fig. 21. Bubble map showing the location of emitters with CO_2 concentrations in the flue gas above 15% with their corresponding volumes.

emitters have CO_2 concentration below 12 %, resulting from open-air combustion of different types of fuels (HFO, crude, diesel, and gas). Fig. 22 summarizes the estimated cumulative volumes of emitted CO_2 corresponding to different ranges of concentrations.

10. Discussion

We carefully verified and cross-checked the collected database with multiple sources, detailing the specifications and production rates of the industrial sectors. As previously discussed, we followed the 2006 IPCC guidelines to estimate the CO_2 emissions from different sectors, which are mostly based on default emission factors. Nonetheless, such emission factors are known to vary widely by country and can be complexly influenced by several parameters such as facility age, efficiency, combustion technology, fuel type, and quality, among others. As a result, a reliable estimate of the main CO_2 emitters is established, showing that the seven primary stationary sources are responsible for about 426 mty

Table 6
Summary of CO2 emissions from the stationary sectors in KSA during 2020.

Sector	CO_2 emission in 2020 (mty)	Contribution to Sum (%)
Electricity	183	43
Desalination	75	18
Petrochemicals	52	12
Refinery*	42*	9
Cement	35	8
Iron and steel	18	4
Fertilizer & ammonia production	21	5
Sum	**426**	**100**

*Estimate does not include Jazan refinery that started operations in 2021; with this facility, the estimate rises to 49 mty.

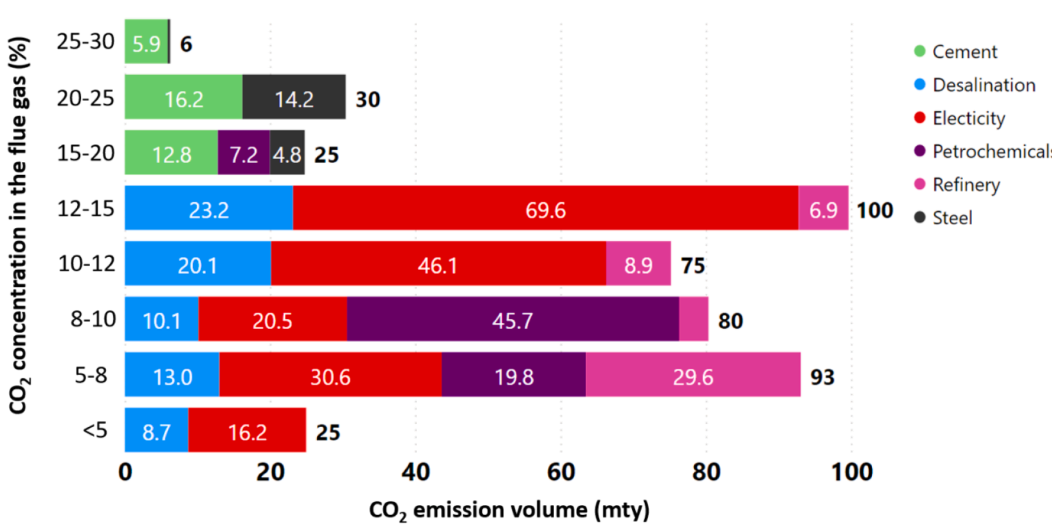

Fig. 22. Estimation of CO_2 volumes corresponding to different concentration ranges in the flue gas for data gathered in 2020.

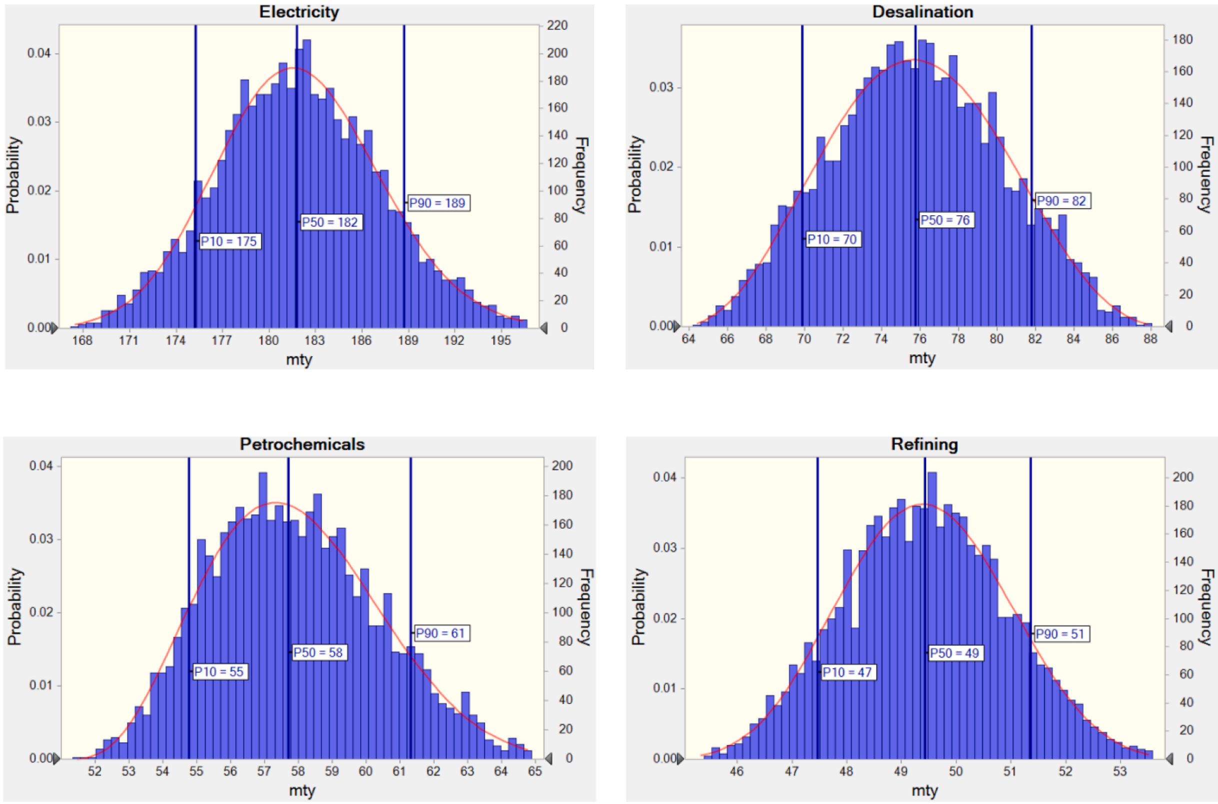

Fig. 23. Uncertainty analysis for CO_2 emission calculation showing the P10, P50, and P90 percentiles for electricity (top left), desalination (top right), petrochemicals including ammonia and fertilizer (bottom left), and refining (bottom right).

(Table 6). On the other hand, the contribution of the remaining sectors, including transportation (road, maritime, and aviation), well testing, and other small emitters (such as agriculture, navigation, fugitive emission from oil production, etc.) are, respectively, 100 mty [27], 5 mty, and 28 mty [3], which add up to the remaining 133 mty. The total emission becomes 559 mty. Note that by including the Jazan refinery that started operations in 2021, the total rises to 566 mty.

The major uncertainty in our calculations is primarily related to the emission factors that we apply. To quantify the uncertainty ranges, we performed probabilistic forecasting using Monte Carlo simulations. We varied the emission factors for each sector within some uncertainty ranges, covering the probable low, high, and most likely values. Fig. 23 shows the probabilistic estimates for the four main sectors: electricity, desalination, refining, and petrochemicals, including fertilizer and ammonia production. The quantified uncertainty for the emissions from the electricity sector, as shown in Fig. 23 (top left), shows a probabilistic range between 178 and 210 mty. The 10th (P10) and 90th (P90) percentiles are, respectively, 175 and 189 mty, while the most likely estimate (P50) is at 182 mty, which is the estimate that we reported previously. Similarly, the uncertainty range [P10, P90] of the other three sectors, desalination, petrochemicals, and refining, are [70,82,55,61], and [47,51] mty, respectively. Fig. 24 highlights the main impactful uncertainty parameters corresponding to the electricity and petrochemical emission calculations.

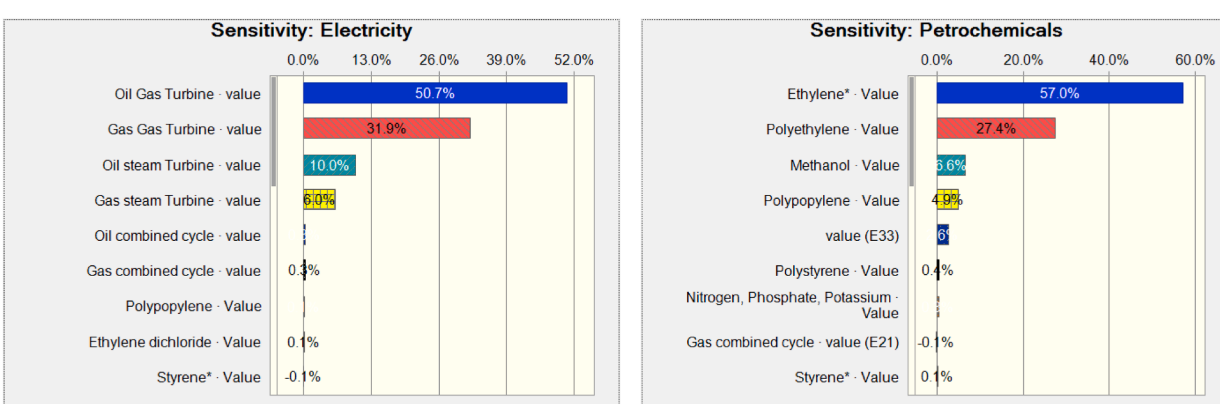

Fig. 24. Tornado charts showing the top uncertainty parameters (emission factors) influencing the emission estimates for electricity (left), and petrochemicals (right).

11. Conclusion

This study provides, for the first time, a detailed assessment of CO_2 emissions from the stationary industrial sources in the Kingdom of Saudi Arabia that are responsible for more than 70 % of the country's total emissions. We compiled geographical maps of the principal emitting sources corresponding to the leading emitting industries, including electricity generation, desalination, oil refining, cement production, petrochemicals, and iron & steel. The collected database includes over 1200 data records for facility details such as the named capacity, production rate, technology, fuel, age, location, and company name, among others. We estimated the CO_2 emissions according to 2006 IPCC guidelines, which are based on defining the emissions factors and the production rates. An assessment of the CO_2 volumetric concentrations in the flue gas is also provided. Such information is valuable to researchers, industry, and government agencies aiming to mitigate GHG emissions by tackling the highest emitting sources by improving efficiency, switching to cleaner energy fuels such as natural gas, and promoting the share of renewables in the energy mix. Furthermore, identifying CO_2 sources is crucial to evaluate the potential and feasibility of CO_2 capture, utilization, and storage (CCUS) in KSA. Our future research aims to assess the potential of CCUS by identifying potential sinks for CO_2, such as subsurface traps that could be located in close proximity to the surface sources.

Data accessibility

The quantified CO_2 emission rates are provided in: Hoteit, Hussein (2022), "CO2 footprint from industrial facilities in Saudi Arabia", Mendeley Data, V1, https://doi.org/10.17632/mmrtv3nnt7.1.

CRediT authorship contribution statement

Ali Hamieh: Writing – original draft, Methodology, Visualization. **Feras Rowaihy:** Writing – review & editing, Visualization. **Mohammed Al-Juaied:** Methodology, Project administration, Validation, Writing - review & editing. **Ahmed Nabil Abo-Khatwa:** Writing - review & editing. **Abdulkader M. Afifi:** Methodology, Validation. **Hussein Hoteit:** Conceptualization, Methodology, Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The link to data has been provided in the manuscript.

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